Operationalism: A Critical Evaluation With An Engineering Problem Case History

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OPERATIONALISM: A CRITICAL EVALUATION WITH AN ENGINEERING PROBLEM CASE HISTORY

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ABSTRACT

This thesis begins with a short biography of the originator of the philosophy of science called Operationalism, P. W. Bridgman. A brief summary of the foundations and basic tenets of the philosophy including some of the difficulties encountered is then given. A justification of such a philosophy and its importance is the topic of the next section. The third part of the paper discusses two completely new methods of measuring contact resistance in thermoelectric devices. Included are: practical considerations, techniques, measurements and results. Finally it is shown that the solution to the engineering problem namely, measuring the contact resistance, is itself a serious objection to Operationalism as it exists today.

PREFACE

I should like to take this opportunity to express my thanks to the people who made this thesis possible, and above all, interesting. Without the cooperation of my advisor, Professor Paul Gray, and the freedom allowed me by the Director of Course XXI, Professor Roy Lamson, this thesis would have been impossible to accomplish. The fact that Professor Gray has been willing to handle a thesis of this type, seeing that he is a memberof the Course VI Faculty, has been gratifying to say the least. I would also like to express my appreciation to Professor Georgi de Santilliana, my advisor from the Humanities Department, for his careful reading and helpful suggestions. Moreover, since I have been allowed to select a topic such as this, my confidence in future cooperation between the Humanities and Engineering has been bolstered greatly.

Other people concerned with this thesis and its preparation are: Mr. David Puotinen for his assistance in obtaining materials and equipment, Professor George Benedek of the Physics Department, a former student and personal friend of Bridgman's, for the time he has spent discussing Professor Bridgman with me, and my wife, for her constant encouragement and, more to the point, for the typing and careful proofreading of this thesis.

INTRODUCTION

This thesis arose in a roundabout way from an interest in its second part, the measurement of thermoelectric parameters. The relation of such measurements to Operationalism was first attempted to justify the existence of the experimental part of the thesis. Now, however, it seems just as important to modify a philosophy of science which has contributed so much to our society, and according to the results here, to present a more accurate case for the grounding of scientific concepts, as to solve the engineering problem itself.

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I. BIOGRAPHY

Percy W. Bridgman was born in 1881 in Newton, Massachusetts. He attended elementary and high schools in the Newton area and entered Harvard University in 1900. He was awarded his A.B. in 1904, A.M. in 1905 and his doctorate in Physics in 1908. Continuing his research in high-pressure physics which was always of interest to him, he made his first real contribution to the field in 1909. This was the discovery of a leak-proof packing which enabled him to build a pressure system which could reach and sustain more than 10,000 atmospheres (150,000 psi.). Even this attainment did not satisfy him, however, for he went on to build equipment and run experiments at pressures of 100,000 atmospheres regularly, and in a few cases, at pressures far above this.

Bridgeman's experiments in high pressure physics far outdistanced the corresponding theoretical work. Today theoreticians are using data that were obtained by Bridgman years ago in attempts to bring theory up-to-date. His data were characterized as coming in "mounds." (31, Purcell) *

Another important contribution to physics (and other disciplines) was his development of a high-temperature furnace. Using either resistance wire or induction heating, the temperature of the furnace jumps from room temperature to above the melting point of the material involved.

* Numbers in parenthesis refer to references listed in the bibliography under the same number.

Finally, in his laboratory in the basement at Harvard, "he made ice that sinks, ice that melts at a temperature higher than boiling water; his pressure equipment caused copper and sulfur to unite explosively, bismuth and tin to alloy and red phosphorus to turn to black phosphorus." (35)

Bridgman's contribution to the literature of science includes sixty papers and six books on the philosophy of science. His major contributions were his Logic of Modern Physics (1927), The Nature of Physical Theory (1936), The Intelligent Individual and Society (1938), Reflections of a Physicist (1950), The Nature of Some of Our Physical Concepts (1952) and The Way Things Are (1959). He also wrote a widely used textbook of physics and a number of other scholarly works.

He became Professor of Physics at Harvard in 1919, Hollis Professor of Mathematics and Natual Philosophy in 1926, University Professor in 1950 and retired as Professor Emeritus in 1954. (35) He was voted Nobel Laureat of physics in 1946 for his high-pressure work.

Professor Bridgman died on August 20, 1961, by his own hand after discovering that he had an incurable cancer and only a very few months to live. He had long before decided that one should choose his own form of death if faced with a predominantly painful future. (34, Holton)
His last words to society were found in a note written on the day of his death; these were, "It isn't decent for Society to make a man do this thing himself. It is probably the last day that I will be able to do it." (34 Holton) It is, perhaps illuminating to know that, on the day before, the Harvard Press received the index to his last book--he

completed the work he had set out to do before he allowed himself to consider his personal situation.

Bridgman was characterized by his enemies (philosophically speaking) as "blockheaded and stubborn" but by most people "as a man of principle," and by a friend as "a tough-minded apostle of ruthless logic ... fierce in his inner disdain of sloppy or wishful thinking." (34, Kemble) He certainly was not stubborn in his philosophy of science for, to him, the term "operation" underwent quite a transformation from its first appearance in 1927 to 1959 in The Way Things Are. This term in its earliest interpretation meant a particular physical operation performed at a particular time, whereas by 1959 it had changed to include mental and verbal operations.

Bridgman's intent was to give physics a solid foundation on which to build its theories. He did not intend to begin a "school" of philosophers nor, originally, to apply the operational definition outside of physics. When faced with the large group of followers he had acquired he said, "I fear that I have created a Frankenstein which has essentially got away from me. I abhor the word operationalism ... which seems to imply a dogma, or at least a thesis of some kind. The thing I have envisaged is too simple to be dignified by so pretentious a name." (34, Holton)

II. OPERATIONALISM

While Bridgman might have wished that his philosophy be of such simplicity, it is evident that even in its basic proposition it is complex. In fact, its foundations can be traced back to Empiricism, Pragmatism and Logical Positivism.

Bridgman devised the idea of operations as definitions for one purpose: that is, to give science and especially physics a solid foundation upon which it could rebuild the edifice of confidence destroyed by Einstein's Special Theory of Relativity. (6, p.1) The characterizations of Operationalism by Bridgman run from a narrow insistence on the physical operation to a much more lax inclusion of mental and verbal operation. The first definition of Operationalism was, in 1927, that "The concept is synonymous with the corresponding set of operations." (6 p. 5) In 1934 he said that meaning can only be found in operations (9 a, p. 103) and in 1938 he discussed the conditions for the determination of meanings, calling operations necessary but not sufficient conditions. (10, p. 116) Finally, in 1952 he said that meanings have more aspects than the one given by the operation. (11, p. 257)

From the above, it can be seen that Bridgman's view of Operationalism changed quite radically as his concepts matured. The last characterization admits of mental, verbal and "pencil and paper" operations as well as those which are strictly physical. The former, however, were never trusted by Bridgman as implicitly as were the latter.

But one may ask, where is his basis for such a trust in the physical operation? To answer such a question, it becomes necessary to look to the foundations of Bridgman's Operationalism.

The first thing that Bridgman does in his Logic of Modern Physics is to establish the empirical nature of science, and physics in particular. He states, "The attitude of the physicist must therefore be one of pure empiricism ... Experience is determined only by experience." (6, p. 3) He admits in his subtitle for the section that "new kinds of experience are always possible," (6, p. 2) but this new experience cannot be interpreted by the results of any other more familiar experience. It must be judged on its own merits. In fact, the physicist must become, to this purpose, a critic of his own experience. He must watch over the interpretations given to his experience by theorists. (7, p. 2)

Bridgman's rationale is evident here. He, first of all, wishes to avoid any more revolutions in physics and, secondly, to establish a system of checks and balances to assure that theorists will not misinterpret nor rate the experience as less meaningful than it is. He points out the kind of thing he wishes to avoid, in his discussion of Newton's absolute time. "Now there is no assurance whatever that there exists in nature anything with properties like those assumed in the definition [of absolute time] and physics, when reduced to concepts of this character, becomes as purely an abstract geometry of the mathematicians, built on postulates ... If we examine the definition of absolute time in the light of experiment, we find nothing in nature with such properties." (6, pp. 4-5)

If we limit ourselves to concepts which we can define in terms of what we can see, feel, taste, smell and hear, or what we can measure, which is merely an extension of sense, then we can, at least, be sure that the concept which we define in terms of these sensibles cannot be completely overthrown. Errors can be corrected, to be sure, but fundamental revision is not only unnecessary but unthinkable. The shock of correction may still be present, but we should be prepared to accept correction as a matter of course. If we define for example, the concept "length" by the set of operations by which we determine length, we can never be said to be completely wrong, as were those who defined length absolutely. A term is defined, Bridgman said, when the conditions under which we can use that term are prescribed and when we may infer from the use of the term by another that he is also limited by the same conditions. (31, Bridgman)

Thus Bridgman is forced to conclude, in accordance with the other empiricists that non-experiential concepts are meaningless; he "recognizes no _a priori_ principles which determine or limit the possibilities of new experience." (6, p. 3) This indicates that we must, in no way, prejudge either the content or scope of our experience; we must take experience as it comes. Traditionally it has been stated that the basic principles of mathematics are _a priori_ (Kant) but Bridgman rejects this along with Locke, Hume and the others. He states that mathematics is "a human invention" (6, p. 60) and "as truly an empirical science as physics and chemistry." (7, p. 52) In his definitive work, A. C. Benjamin classes these statements as "perhaps incompatible." (5, p. 18) But it seems as though these statements (including the first) can be thought of

as equivalent, meaning that mathematics arose (just as did physics) invented by men, as an aid in understanding experiential nature. Incompatible or not, however, both statements ground mathematics in experience, and reject the a priori. But Bridgman does not give further explanation of how to reject the rest of the traditionally a priori ideas.

With his rejection of the a priori, Bridgman begins his attempt to reconcile the objectivism he feels to be necessary and the creativity he feels the scientist gives to his experience. On the one hand he says "the only possible attitude toward the facts of experience as it unrolls is one of acceptance." (7, p. 15) On the other hand he argues for the relativity of knowledge, and the relevance of the human viewpoint. (11 a. p. 5) Much more to the point, Bridgman says "I can never get outside of myself; direct experience embraces only the things in my consciousness--sense impressions of various sorts and various sorts of cerebrations--and naught else ... science is only my private science ... 'public science' is a particular kind of science of private individuals." (7, p. 14) Further along he states ... "every individual must be his own judge of what he shall accept to be satisfactory evidence of competence in another." (7, p. 14) This position is thought by Bridgman to be solipsistic (a philosophical position that all one's experience, including the secondary way of experiencing through the experience of others, is a product of one's mind) and concluded that "we have got to adjust our thinking so that it will not seem repugnant." (7, p. 14) Bridgman, moreover, was never able to reconcile these two positions in his later writings.

In his objectivity, however, Bridgman was an extremist. He completely restricted the operation to a set of particular circumstances. These circumstances completely define the concept and, in fact, a particular concept, never the universal. In his emphasis on particularity Bridgman follows the narrow interpretation of empiricism. He says "Operations are performed by human beings in time and are subject to the essential limitations of the time of our experience--the full meaning of any term involves the addition of a date--future operations mean nothing except as they are described in terms of operations performed now." (7, p. 16) Some authors would interpret this statement as meaning that operations are not strictly repeatable, (5, p. 20) but it would seem that another interpretation is more believable. We might understand Bridgman as saying here that future operations must be described in terms of primitive operations (those upon which primitive concepts depend) and these operations, it must be realized, are performed now, being based on other concepts defined by past operations; neither the present or past operation can be assumed to be valid in eternum.

The main emphasis on particularity which should be brought out here is Bridgman's description of two operations which are, by their very nature, different and which have as their definiendum the very same concept. He says:

> If we deal with phenomena outside the domain in which we originally defined our concepts, we may find physical hindrances to performing the operations of the original definition, so that the original operations have to be replaced by others. These new operations are, of course, to be so chosen that they give, within experimental error, the same numerical results in the domain in which the two

> sets of operations may be both applied; but we must recognize in principle that in changing the operations we have really changed the concept, and that to use the same name for the different concepts over the entire range is dictated only by considerations of convenience, which may sometimes prove to have been purchased at too high a price in terms of unambiguity. (6, p. 23)

The second school from which Operationalism takes some basic ideas is Pragmatism. The main pragmatic tenets used are a great emphasis on workability and an expressed need for clarity.

Bridgman would take issue with one part of the clarity issue and that is the pragmatic unity of ideas. Bridgman insists that we can never had the same concept defined by different operations. At some time in the future the concepts may be shown to be equivalent, but this can only be shown by an operational test. "Thus when we use operations to clarify all concepts, and when these operations have themselves become conceptualized we use further operations to clarify them." (5, p. 34) Thus the only appeal open to us is the operation.

Bridgman's pragmatism also declares that the operation must be performable. His attitude is one of "let us try it and see." If the operation is not one which works in the laboratory then all we can say about the concept is that it is <u>not</u> defined by this particular operation.

Truth, however, is treated somewhat differently, by Bridgman, than by other pragmatists. Dewey, for example, accepts the operational nature of definitions (16, p. 111) but for him the truth of a statement consists in a realist's sense of "correspondence"; that is, a statement is true when it corresponds to external reality. For Bridgman, a statement is true only

after the operation has been actually performed and shown to have results which confirm the statement. Statements prior to the operation cannot be adjudged true or false, but only meaningless. In his discussion of this subject he mentions the problem of the transcendental nature (a root of no algebraic equation) of π. "The proof that π is transcendental was given in 1882. In 1881 was this a true statement, 'π is either transcendental or it is not'? The operational position must be that this was not a true statement in 1881, but that it did become true in 1882." (7, p. 43) Notice here the validity of the mathematical proof of the transcendence of π -- a pencil and paper operation.

From the stricter form of Empiricism, that of Logical Positivism, Bridgman draws his rejection of all things metaphysical. A metaphysical statement is meaningless to Bridgman as is a statement of a mystical or theological nature. He also attempts to eliminate the "unnecessary" concepts in the world, defining these as the ones which cannot be tested operationally.

Now that we have seen something of the background of Operationalism, let us try to expose the presuppositions that underlie all of Bridgman's philosophy. It is by this method that modern analysists begin to see the weaker points of any philosophy they are trying to dissect.

The _basic_ presupposition that Bridgman makes is that experience is the only source and the ultimate guarantee of knowledge. (5, p. 13) Sensation has always been criticized by philosophers as incapable of testing fundamentally basic ideas. From Bridgman's point of view,

experience is sensation plus activity; there must be some kind of doing to determine what we mean by an idea we express. For Bridgman there can never be any meaningful idea that is not operationally actively defined. The concept "length" has no meaning apart from the operation used to measure it. When this word is used non-experientialy then we can no longer be sure what it means. If my neighbor says "My hasn't it been a long day," I might not agree at all. I might feel that the day has been all too "short." The use of the word long here certainly conveys some idea that my neighbor is tired, bored, or somehow or other affected by the day's passage, but I can never be quite sure in what way, or how "long" the day has been for him.

Another presupposition that must be examined is Bridgman's purpose in presentating Operationalism. Is he trying to describe the process of obtaining trustworthy knowledge in science, or is he presenting a way of knowing in general? The later Empiricists have taken the latter view and developed Operationalism from that point. Bridgman, however, emphasized that he only means to do the former and is quite emphatic in his denial of other intent. (10 a., p. 114) The conclusion should be, then, that Bridgman has the attitude of the experimentalist here also; he seems to feel that to try to apply the results of such a philosophy of science can only result in something better happening to the "scientific method." It is not to be a static or absolute philosophy, but one which seeks critical analysis especially in the field where it is strongest and most confident, the concepts of the scientist. Bridgman felt that other disciplines, for example the social sciences, might well benefit by some

criterion such as the operation, but it was not his purpose to establish one for anything but science.

The operation then is Bridgman's most basic idea. It is a performable activity by which we can define a concept with the reasonable certainty that we will not be shown to be completely "off base" at some time in the future. The operation defining length is the method of measurement, i.e. meter stick length, triangulation length, optically measured length, etc. Moreover, mass is defined, by the type of operation, as gravitational mass or inertial mass. If operation can actually be performed to define the concept, then, any statement about the concept is meaningless. Until the existence of anti-matter particles was demonstrated in an experiment, statements about this concept could neither be said to be true nor be denied; and when this is the case, the statement should be treated as meaningless chatter by ignoring it. When the operation was finally performed,then something said about the concept could be adjudged as true or false.

The "operation" has been defined, however, by some of those who took up Bridgman's point of view as specifying the procedure for identifying or generating the definiendum and finding his reliability for the definition. (15, p. 482) Others have said "We say of a scale that has been standardized to measure public opinion, 'Public opinion is what this scale measures.' This is then the operational definition of the concept public opinion." (14, p. 156)

But this last definition is merely a tautology. If we substitute the words "dingle factor" for "public opinion" that statement is just

as meaningful as it is in its present form. But even Bridgman realizes how close one comes to tautology if one tries to specify too much about the operation; and,if one tries to avoid tautology by saying less, he finds that he says nothing worthwhile.

As can be seen from the above, the term "operation" can have different meanings for many people. The meaning, for our purpose here, will be taken as Bridgman meant it in his later writing; i.e., the operation is an activity, either physical or pencil and paper, by which we define a concept. These activities are listed in descending order of trustworthiness and the physical operation is always preferred.

Now that we have defined the term we can go on to the discussion of the difficulties one encounters when trying to use this philosophy.

In the first attempt to use operational definitions, one finds himself restricted to defining a "here and now" concept. One can define a particular length or a certain mass under the conditions prescribed by the present time and location. One cannot say that one is measuring length or mass, only that these measurements are applied to this length or this mass.

An example of the reductio ad absurdum of operationalism's insistence on particularity is given by Franz Alder. (1, p. 440) He suggests that we try to define, operationally, a certain concept which he calls "C_n" to avoid confusion. The operation is the summation of values obtained by listing and scoring the response of an individual to certain questions. These questions ask for the number of hours of sleep on the previous night,

his opinion of fried liver, the estimated length of his nose, whether his grandmother cooked red cabbage with apples, etc. The "C_n rate" is computed from a very long series of these answers involving highly complex mathematic formulations including the number of weeks the test is repeated, the number of individuals involved, environmental effects, correction constants and further considerations. The resulting function is a most complex one involving many of the mathematical tools with which the scientist is familiar, and, really looks like a "carefully derived scientific concept." But what is the concept? Pure and unadulterated nonsense! Yet we have operationally defined C_n.

So it looks as though there must be some other criterion applied rather than particular operations. Bridgman never discusses what else is necessary in deciding whether the operations really do define a meaningful concept, and how the decision is made. Is this also done operationally?

The operation, according to the emphasis on particularity then, is not repeatable in the strict sense, but only approximately so. Thus it is impossible to define general concepts operationally and these must belong to the realm of metaphysics or other areas equally mysterious. Science, however, uses general terms as frequently and with as much confidence as do the other disciplines. Therefore, any philosophy of science must allow general terms and indeed must set some criterion to determine their value.

The second difficulty in this area, which follows from the above, is

the multiplication of concepts by different operations, and this is the difficulty with which this paper is primarily concerned. Bridgman felt that one could not define the same concept with two different operations; gravitational mass and inertial mass are measured differently, so they should be presented as different concepts by using the specific prefix. In fact, even if the two operations should prove to be identical in the future, the distinction must still apply. The following is Bridgman's own statement of the case:

> We must always be prepared some day to find that an increase in experimental accuracy may show that the two different sets of operations which give the same results in the more ordinary part of the domain of experience, lead to measurably different results in the more unfamiliar parts of the domain. (6, pp. 23-4)

It would seem, however, that Bridgman is avoiding part of the responsibility that he assumed when he espoused Positivism. It is the attempt of this philosophy to get rid of all unnecessary concepts in accordance with the principle of Occam's Razor. A philosophy of science should, it seems, pare the conceptual kingdom to the core of basic essentials rather than invent a multiplicity of concepts to correspond to each item of experience.

This brings us to the third difficulty we encounter with Operationalism's basic postulates; they are not complete enough to carry out the practical application of Operationalism.

Bridgman has not nor indeed have any of his followers even attempted to classify operations beyond his "physical" and "pencil and paper"

distinction. But in some cases it seems there cannot be a separation between the two types because they are both involved in defining a concept. It is impossible to make any judgment, moreover, on the goodness or badness of our operations, which Bridgman uses as his criterion for trustworthiness because we have no rules to follow. (10 a., p. 126)

Furthermore, there has nowhere been made a distinction between symbolic and non-symbolic operations. Certain operations produce symbols or give meaning to symbols (such as the height of a column of mercury in a thermometer). Other operations are non-symbolic, especially physical operations, such as the determination of the temperature of a gas. It can be seen that these two operations are not quite the same, yet is one more trustworthy than the other? We don't know what answer Bridgman would give.

In spite of the incompleteness of Operationalism, it is quite evident to the scientist and engineer that it is a step in the right direction. Scientific concepts do need some grounding philosophy to determine which concepts are to be trusted and which rejected. Bridgman refused to classify his operation as a basis for a theory of knowledge, yet a theory of knowledge is needed for science.

Certain tenets of Operationalism are being used in practically every phase of science. It becomes evident in physics in the many operational prefixes one finds and it has been said by an electrical engineer that

"we go along with Bridgman in some ways." * Even in such an unlikely place as the Proceedings of the Institute of Radio Engineers one can find reference to Operationalism. In an article on circuit theory the following appeared: "We ask not only that a set of conditions (for a given type of network) be sufficient but also that it be operational, in that the conditions actually prescribe a means of synthesis for the network in question ... Furthermore ... that the conditions be stated in a form readily tested ... ." (36, p. 866)

An attempt to present a modified Operationalism has been made by A. C. Benjamin. (5, Chap. VI) He gives fourteen points which must be considered by any "generalized Operationalism." The emphasis on clarity and certainty must be retained of course, but knowledge is more than experience, there must be room for both induction and deduction, (scientific theory contains both). Further the workability of the operation is a natural criterion for validity. Benjamin would like to include in the idea of workability the distinction between "operationally defined constructs" or concepts derived from actual operations, and "hypotheses", and to allow the latter at least some value as potential constructs. The operation has its place in this theory of knowledge as the "activity performed" on the "something to be known"; thus all non-operational thinking is "impossible by definition." (Benjamin's use of the word operation here differs little from the later Empiricists use of the word experience. If non-operational thinking is impossible, how can he

* Statement of Professor Paul Gray at oral presentation of this thesis.

explain metaphysical or religious thinking unless he wishes that these too are called experiential? Some people would agree, if this is the case, that metaphysics is grounded in experience but is an abstraction from it.) The operations are classified, unlike the present situation into discriminating, ("inspecting," "discovering," and especially "tagging") which creates a symbol; associating, by which names for things are devised and given meaning by combining particulars; generalizing, whereby "classes are associated by resemblance"; and ordering, by which series are symbolized and defined. Benjamin's last point, the most important as far as we are concerned in this paper is that measurement has a two-fold nature. He calls the first the "fundamental" measurement which does not depend on other measured values for its "metricization," and the "derived" measurement. The fundamental measurement would indeed require the creation of a new concept of each operation, but the derived measurement is only an alternate way of measuring a concept already introduced.

In the next section of this paper, we shall show that this distinction should indeed be made at least in one special case, and that the two completely different operations we perform do indeed define the same concept. Thus this paper attempts to show a basic operational test of one of Bridgman's main points.

III. ENGINEERING PROBLEM

Before entering the main body of the problem with data evaluations and necessary mathematics, it is no doubt apropos to introduce the reader to the field of thermoelectricity.

In the 19th Century it was noticed that certain metals exhibited some rather strange properties. These could be made to establish a temperature difference between their ends if an electric current were passed through them. The sign of the temperature drop was a function of both the type of metal and the direction of the current. Moreover, if a temperature drop were imposed across the metal (e.g. by heating one end) then electric power could be generated if it were electrically connected to some resistive load. Later the same property was exhibited by materials which were neither conductors nor insulators of electric currents. These materials were called semiconductors, and the strange property noticed in the metals earlier was greatly enhanced in them. When it was found that the semiconductors could be made to show these properties in a controllable way by adding small amounts of impurities (called doping the material) a practical future application was foreseen for them. When a semiconductor is doped with an electron supplying material, the temperature drop across the material induced by a current is in one direction. When a "hole" producing dope (that is an impurity with a vacancy in its valence ring) is added, the temperature drop is in the opposite direction for the same current direction. Thus it was seen that by doping one piece of semiconductor with electrons (n-type material) and another with "holes" (p-type material) and putting the pieces together

electrically and thermally, a much larger temperature drop could be induced by a current, or much more electrical power supplied by heating the end of such a device.

The devices which perform these two functions are called respectively thermoelectric pumps and thermoelectric generators. See Figure 1.

The heat pump shown in Figure 1 in accordance with the Seebeck effect absorbs heat at the upper junctions and gives off heat at the lower junctions thus setting up the temperature difference. The equations defining the Seebeck coefficients at the junctions are, in differential form

$$\alpha_c = dV_o/dT_c \qquad 1.1$$

$$\alpha_h = dV_o/dT_h \qquad 1.2$$

where the subscripts c and h refer to cold and hot junctions and Vo is the open circuit voltage measured across the heat pump. In the heat pump we are interested in the temperature drop when we impress a voltage across the sample by passing a current through it. In the generator we are interested in the voltage drop when we impress a temperature difference between the ends by heating one of them. In this paper we shall limit discussion to the heat-pump device.

The problem that we shall attempt to solve here is to devise a method to measure the resistance created when the two types of semiconductors are joined by means of a conductor. This so-called contact resistance appears even when we join two conductors together, but most of the time

it is too small to measure accurately. The resistance in a semiconductor-conductor contact theoretically should be independent of the area of the contact but in fact is not. (27, p. 161) The larger the area of the contact the greater the probability of getting some area of poor contact.

The high current densities required in a device of this type demand a fairly large area for the contact, and this is one reason why the contact resistance for these devices is 2-3 orders of magnitude greater than soldered copper contacts, and thus easily measurable.

Contact resistance is undesirable in a thermoelectric heat pump for a number of reasons. First of all, the contact resistance wastes power which could otherwise be used for refrigeration. The power wasted is

$$P_w = I^2 R_c$$

Since the current I is large, even small values of Rc cause significant wastage. Even more important, the wasted power appears in the form of heat at both contacts. We would not mind more heating at the hot contact, but at the cold contact any heating effect is undesirable. If the contact resistance is large, then the I^2R heating can completely negate the Peltier cooling. *

It can be seen therefore that this problem has a practical nature as well as applicability to this thesis. If we can measure the contact resistance accurately, we can then begin to evaluate materials and methods of making contacts to minimize the resistance. The measurement applies to the thesis because we shall use two methods of measuring contact

* Most of the devices built here at M.I.T. for B.S. theses projects have failed to work for this reason.

resistance in this case. The methods used are not equivalent and it shall be demonstrated, operationally, that these two operations define the same concept.

Previous attempts to measure contact resistance have varied from the sublimely sophisticated to the extremely naive. Engineers concerned with the problem have concentrated, for the most part, on the instrumentation necessary to measure small values of voltage, and this is important for small resistance. The contact resistance has been measured in most cases by a voltage vs. distance tabulation and graphical plot with a microscope to determine the location of the conductor-semiconductor interface (the graphical discontinuity at the contact is R_c). Other techniques have used a sliding probe to plot voltage vs. distance measurements on an X-Y plotter and then extrapolation to find the contact resistance; (19, p. 144) in another case the measurement was made by attaching probes to the material and measuring the voltage on the probes. (17, pp. 1-4) Other less sophisticated techniques have included measuring the total resistance of a semiconductor, then remeasuring the resistance after it has been cut and a contact inserted. (27, p. 161) An even more naive method is merely guessing at the value from device performance. (17, p. 5)

When one inspects each method closely, one finds inconsistencies in the reported data that lead the engineer to mistrust the entire method. In today's most widely used method, the basic procedure depends on exact knowledge of the location of the contact interface. The contact must be located exactly because we measure the voltage drop between the

conductor and the voltage probe. Any material between the conductor and the probe will add a substantial voltage drop to that caused by the contact resistance. The voltage drop caused by the semiconductor material cannot be known very accurately because of the material's inhomogeniety. Thus the accuracy of R_c depends heavily on the accuracy of the location of the contact. This has been published as certain within 0.02 mm. This figure indicates a measurement uncertainty of .02 mm times the electrical resistivity of the material (10^{-3} ohm - cm) or $\pm$ 2 x 10^{-6} ohms. However, this accuracy presupposes that the interface is in the same vertical plane all across the end of the material. This is not necessarily the case because of bubbles in the solder, plating overlap, flux layers between the solder and semiconductor, and damage to the semiconductor face because of heating. One, therefore, must ask whether it is absolutely necessary to determine the location of the interface with more than nominal accuracy.

The results published for the first of these methods have stated a measured contact resistance of 1 micro-ohm $\pm$ 5% with typical values of 10 micro-ohms. When one reads further in the report, one finds that the value of contact resistance varied by $\pm$ 100% as it was measured in different planes around the periphery of the semiconductor. (27, p. 157)

The methods proposed herein by-pass the problem of locating the contact interface, and thus should be more useful in the long run. The instrumentation required for the first method is uncomplicated and should be available to <u>any</u> organization that is engaged in research

along these lines. See Figure 8. The second method does require more extensive instrumentation and more care in the actual operation.

The semiconductors used in these measurements ($Bi_{2}Te_{3}$ Iodine doped - No. 1053 and $Bi_{24}Sb_{72}Se_{6}Te_{138}$ quatenary lead doped No. 1084) are commonly used materials for thermoelectric cooling devices. See Figure 2 for a sketch of the semiconductor ingots. The ingots were cut with a high-speed rotary diamond wheel cutter with water cooling. (The ingots were cemented on 1/4 inch plate glass strips with sealing wax). After cutting and discarding shattered pieces (No. 1084 was extremely brittle, also see Figure 3 for cut on No. 1053), we melted the potting wax from the material with a room temperature bath of a 50/50 acetone and alchohol mixture.

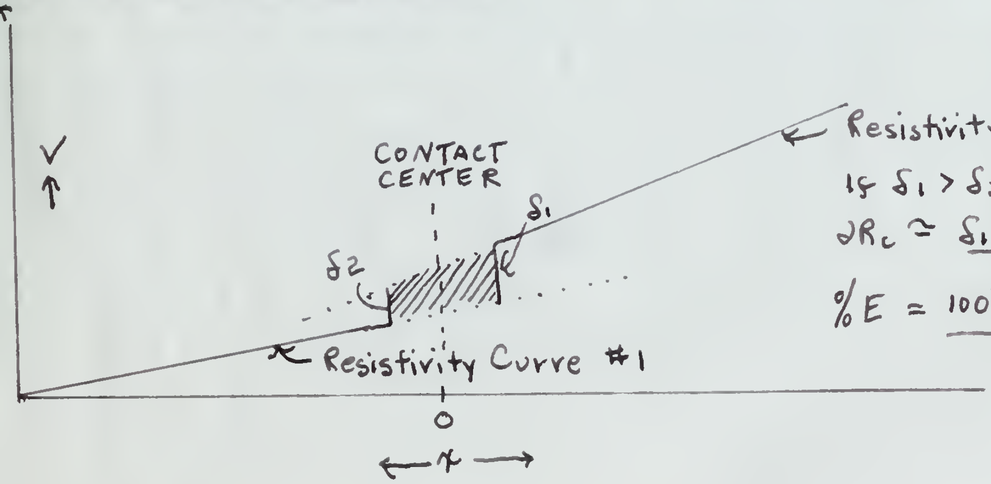
The semiconductor slices were then lapped on a water-wetted polishing plate until the ends were polished bright. The material was next washed with tri-chlorethylene, sandblasted, washed in succession with acetone, alchohol, distilled water and again with acetone. The last step was to remove any trace of grease of fingermarks over which nickle plating will not take. The samples were electro-plated until a nickle layer of a few mils thickness was estimated (from reaction rate) to cover the end of the semiconductor. This plating is another source of error, caused by the nickel overlapping the end of the material and forming a conducting layer around the outside of the semiconductor confusing contact location.

The next step in the preparation of the material was, at first, wetting the ends of the plated semiconductor with 60/40 lead-tin solder.

(Later in the process we discovered that, before soldering, the length of the material must be measured) After wetting the ends, the material and a tinned contact were placed in the soldering jig designed and built for this purpose. See Figure 4. Again, later in the process, we discovered that the solder joint was better if the pressure upon the couple while soldering was just under that for material fracture, so we did subsequent soldering in a press, increasing pressure as the contact was heated.

The first runs were discouraging because inadvertently we had obtained material of extremely different volume conductivities. At this point the resistivity curves were being extrapolated to the edge of the contact on either side and the discontinuity was measured at that point. The discontinuity then is a function of the slope of the line and total distance between the actually measured voltages. The method was not yet sophisticated enough to handle a difference in conductivities greater than 2. A geometric analysis was made to determine the error induced as a function of conductivity differences and this showed a limitation of the factor of 2 for 10% error.* As we shall soon see, this limit no longer holds.

*



if $\delta_1 > \delta_2$

$\partial R_c \simeq \frac{\delta_1+\delta_2}{2}$

$\% E = \frac{100\left[1 - \frac{\delta_1-\delta_2}{2}\right]}{2}$

Originally, the method merely extrapolated the voltage-distance plots from each side of the contact to the other and at one side of the contact the measured difference between the curves was thought to be the contact resistance. Immediately,upon entering the operation, the geometrical aspect of error loomed large. After further analysis, it was decided that when one came across two pieces of semiconductor with exactly the same conductivities or cut one piece in two, then this method could be used to measure the contact resistance.

At some point or other in the process, it was decided that we could avoid the problem encountered above by measuring both the thickness of the center contact and of the solder. The center contact and the semiconductors were measured with a micrometer in the normal way. The solder thickness was measured by adding up the above lengths and subtracting these from the total length of the "couple" measured again with the micrometer.

When the curves (linear) are plotted, either the portion to the right of the contacts is translated left for a distance equal to the sum of the lengths of the contact and the solder, or the portion on the left, is translated right by the same amount. See Figure 5. The discontinuity then is measured between the first measured point of the contact of one curve to the first point on the translated curve.

The contact resistance measured here is actually the sum of the resistance of both contacts, thus the measured value is the average of the two. It is assumed here, however, that the average contact resistance

will be close to the true value because of the method of making the contact.

One of the results of the final technique is presented in Figure 6. The total contact resistance measured here was $216 \pm 10 \times 10^{-6}$ ohms giving an average resistance of 108 ± 5 micro-ohms.

The error factors here are functions of instrument errors and graphical uncertainties. Instrument error can be held to ± 2% current error, ± 2% voltage error, ± .1% position error. The graphical error arises when one draws the best fit straight lines through the non-linear resistance-distance curves obtained. By strict mathematical methods, * this error should be containable within 2%. Then the total estimated error is approximately ± 6%. This method, however, will avoid the variations of contact resistance with the plane measured, so the total error here, while slightly greater than published figures for other methods (± 5% Mc Connell and Sehr), is less than the errors caused by orientation effects (variations in measured resistance as a function of the vertical plane used to measure it).

The second method of measuring the contact resistance is conceptually quite different from the first. It is a measurement of the initial rate of

* For example the method of least squares which says "take as the line ... of best fit that one for which the sum of the squares of the deviations ... is a minimum."

Cf., Thomas, G. B., Calculus and Analytical Geometry, Reading, Addison-Wesley, 1951, pp. 512-515.

cooling of the cold junction of the heat pump when a current step is applied to the thermoelectric couple. See Figure 1. This method stems from the doctoral thesis of Paul E. Gray (20), where the equations describing the transient behavior of the heat pump are derived.

As a result of the above work, we know that the rate of change of temperature with current has the following dependence:

$$\left.\frac{dT}{dt}\right|_{t=0^+} = \frac{\alpha I T_c}{C} - \frac{2 R_c I^2}{C}$$

where . α = Seebeck Coefficient in $\mu V/{}^oC$

I = Current

T_c = Temperature of Cold Junction at $t = 0^-$

C = Thermal Inertia of Contact

$2R_c$ = Contact Resistance (total)

if we let $dT/dt = M$

and plot M/I vs I

we get $$M/I = \frac{\alpha T_c}{C} - \frac{2 R_c I}{C}$$

and Slope $$\frac{\partial (M/I)}{\partial I} = -\frac{2 R_c}{C}$$

Thus by plotting out the curves we find the thermal resistance (C) by locating the intercept of the curve; knowing C and the slope of the line we calculate R_c.

The Seebeck coefficient can be measured either by establishing a temperature drop across each leg in turn and measuring the voltage generated, or by using an "alpha probe" and averaging over many measured

values (the alpha probe measures α only in a very small area).

Temperature measurements were made with chromel-alumel thermocouples and a Keithley Micro-Volt Ammeter. The Keithley instrument has an output amplifier which will deliver a voltage proportional to the deflection of the voltmeter. This voltage was fed into a Texas Instruments 0-5 ma recording galvanometer where we recorded the temperature in the form of a line inked on a moving chart. See Figure 9.

As mentioned above, this method required better instrumentation than the first. The device holder must be more complex;and, to avoid problems that could arise here, we used the same holder designed and built by Paul E. Gray. (20, p. 68) The temperature of the cold junction was plotted on the recorder; the current step was applied with a switch and measured on a .1% ammeter, then recorded on the chart.

It was discovered upon trying to analyze the first set of data that a 20% error could occur when measuring the slope of the temperature vs. time curve using ordinary tangent lines. A device called a tangentometer was constructed to avoid this error. A tangentometer is a mirror mounted perpendicular to the leading end of a straight edge. See Figure 9. The mirror is placed on the curve and the image and curve are linearized by the eye, then a line is drawn along the straight edge. The line resulting is accurate to within one degree of arc ($\pm$ 2%) with the constructed device.

The first set of data was analyzed and resulted in a figure of 75

micro-ohms for the total contact resistance of a demonstration device located in the Energy Conversion Laboratory. This gives an average contact resistance of approximately 38 micro-ohms which is a reasonable figure, although the slope error above made the data highly uncertain.

In order to come to any meaningful conclusions about the identity of the concepts that these two operations define, we had to perform both measurements on the same device.

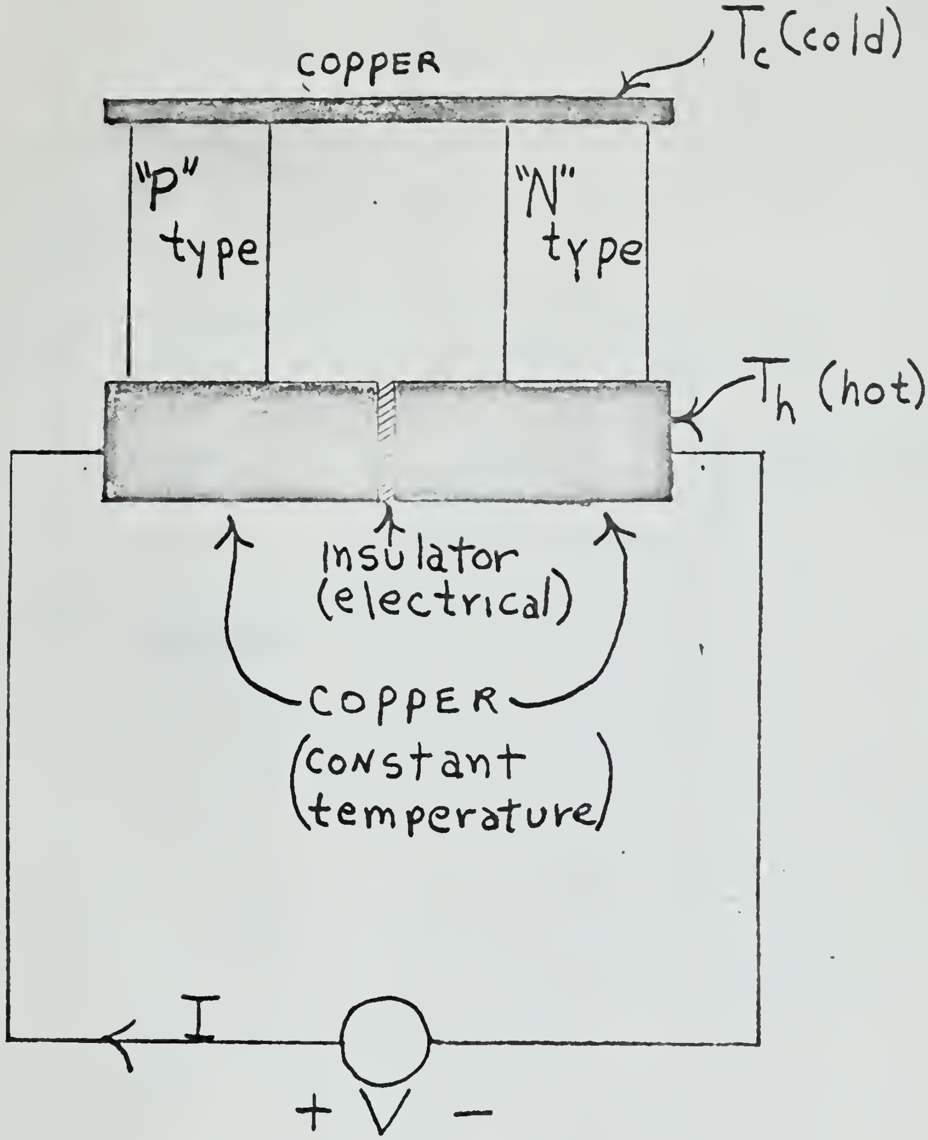
A couple was prepared for this purpose and put to the test. The resistivity of the "p-type" material was, unfortunately, much greater than the "n-type," so that the possibility of error is much greater. However, the first method gives an average contact resistance of 108 $\pm$ 10 micro-ohms measured along two planes and the second method gives a result of 121 $\pm$ 10 micro-ohms per contact. The error in the second method is inherently greater than the first though not necessarily so. The $\pm$ 10 micro-ohm figure given for the uncertainty in this measurement was calculated from the following considerations. The Keithley meter is $\pm$ 3% full scale accuracy; the Texas Instruments galvanometer error is 2% and the slope measurement is 2%. This gives a total uncertainty of $\pm$ 7% over-all. There is, however, an error introduced by the ammeter at small current (5% at 1 ampere) and by convection effects on the cold junction at small temperature changes (uncertain) causing a distrust of values plotted at small values of current. This has not been included in the error figures but has been included in the uncertainties plotted on Figure 7. The slope difference involves a difference between the mean and average value of the discontinuity measured on Figure 6,

thus introducing a further uncertainty of 5%. However, the values measured with the two methods do agree as can be seen, and this agreement is well within the error limit set above.

It is unnecessary to point out here that this result is one more thorn in the side of Operationalism as it now stands. Two different concepts of contact resistance are not required here although the defining operations are different. Bridgman insists that,however close the measurements come in numerical value, if the two operations are not finally reducible to one, then two concepts are necessarily defined. Here, he would say, one method defines "ohmic contact resistance" and the second defines "watt-second contact resistance." The engineering problem above shows the numerical result to be the same (within the error figures). It also shows that one simple concept "contact resistance," is all that is needed to explain the numerical equivalence. Benjamin would call the first method a derived operation and the second fundamental, and this seems to resolve the objection quite well.

It probably is already evident to the scientists that Operationalism has contributed greatly to clear thinking in their discipline. It would be a benefit, therefore, to science and engineering if someone devised a modification of Operationalism to answer any serious objections. Mr. Benjamin's suggestions as listed above will make an excellent starting point for any improvements.

In conclusion, let it be remembered that this paper is not intended as a sweeping denial of Operationalism's usefulness as a philosophy of science. Bridgman has taken the first steps to give science a foundation which is reasonable and trustworthy; and it remains for us, his students, to perfect his method.



Thermo electric Refrigerator

Fig 1

Sample Configurations
(side view)

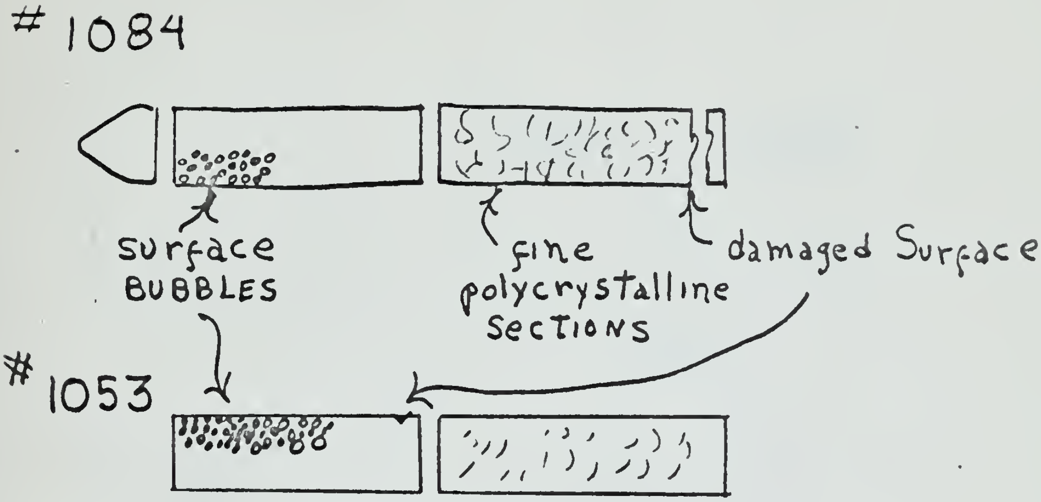
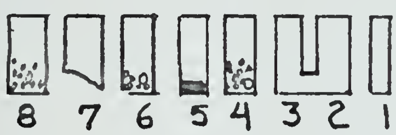


Fig 2

#1053 after cutting



5&7 fractured while cutting
2&3 not cut through
(finished by sand blasting)
2 fractured while soldering

Fig 3

SOLDERING JIG

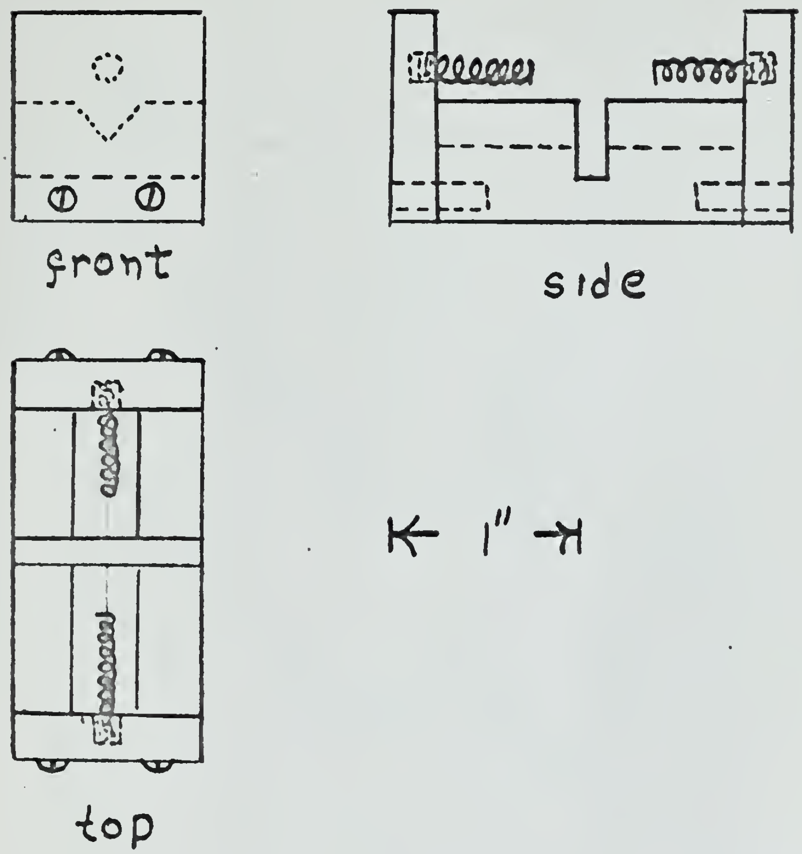


Fig 4

Discontinuity Measurement

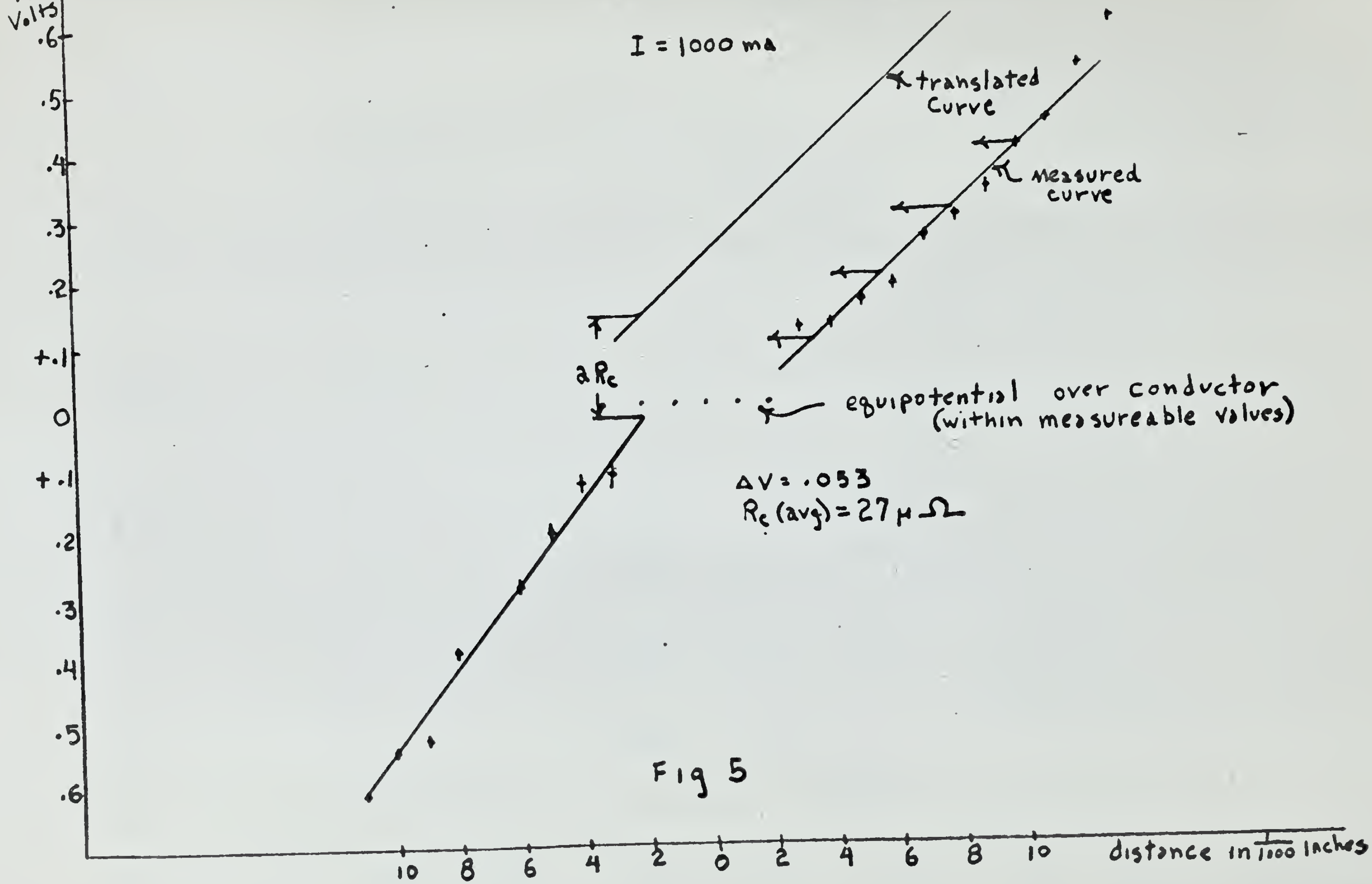


Fig 5

Discontinuity Measurement

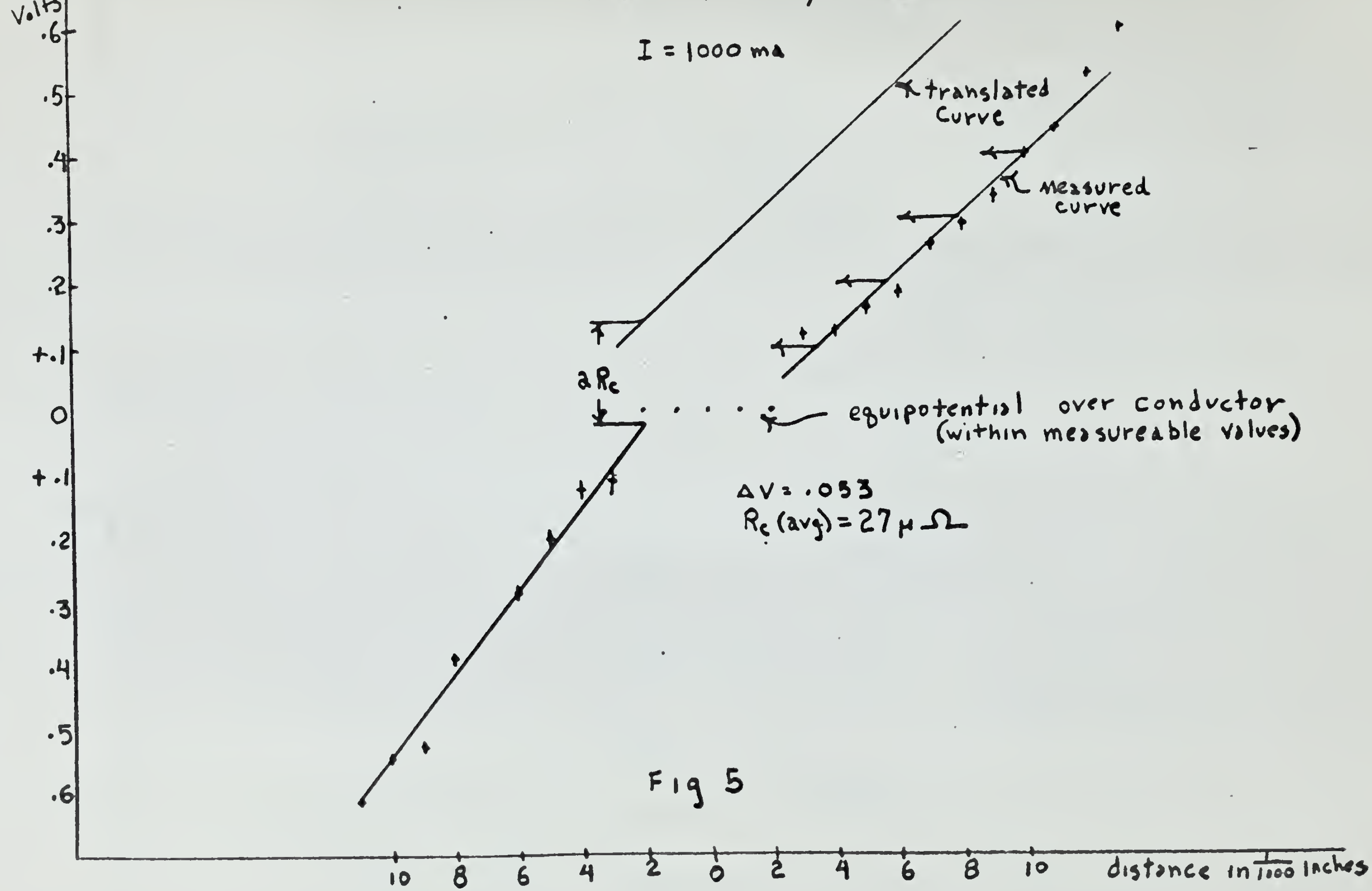


Fig 5

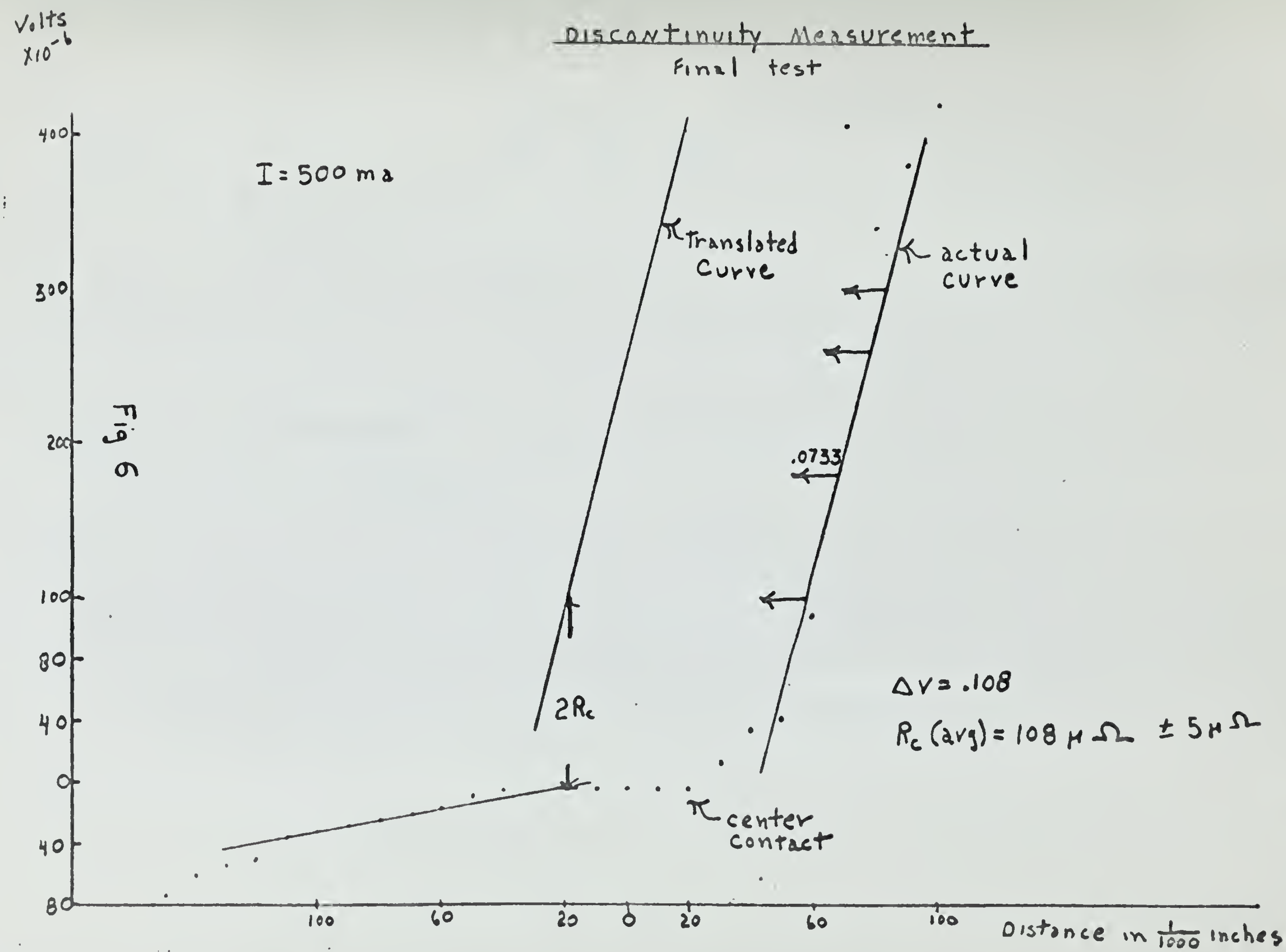

Discontinuity Measurement
Final test
Volts $\times 10^{-6}$
I = 500 ma
Translated Curve
actual curve
.0733
$2R_c$
center contact
$\Delta V = .108$
R_c (avg) = 108 $\mu\Omega$ ± 5 $\mu\Omega$
Distance in $\frac{1}{1000}$ inches
400
300
200
100
80
40
0
40
80
100
60
20
0
20
60
100

Fig 6

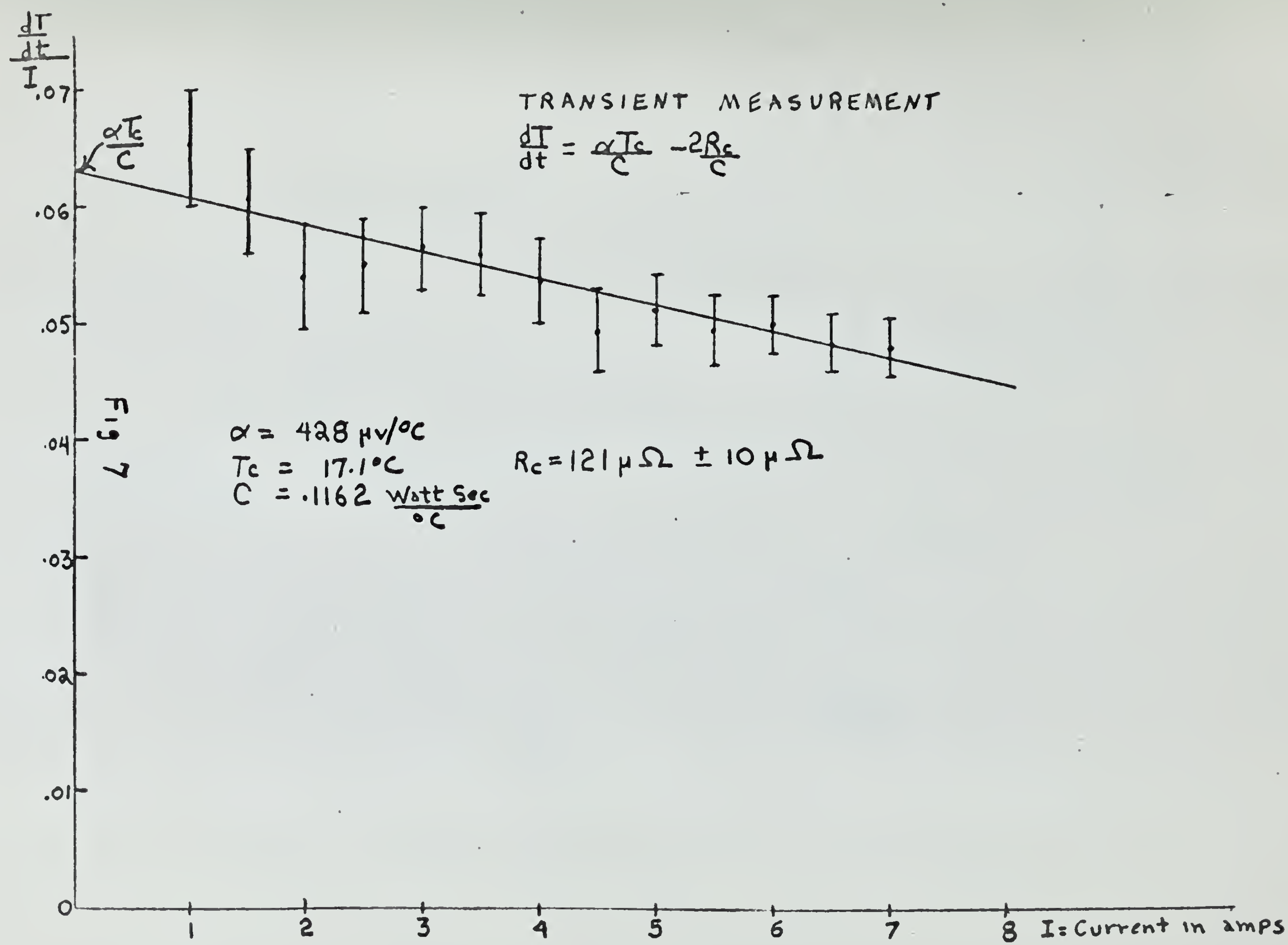

TRANSIENT MEASUREMENT
$\frac{dT}{dt} = \frac{\alpha T_c}{C} - \frac{2R_c}{C}$
$\frac{\alpha T_c}{C}$
$\alpha = 428\ \mu v/^\circ C$
$T_c = 17.1^\circ C$
$C = .1162\ \frac{\text{Watt Sec}}{^\circ C}$
$R_c = 121\ \mu\Omega \pm 10\ \mu\Omega$
$\frac{dT/dt}{I}$
.07
.06
.05
.04
.03
.02
.01
0
1
2
3
4
5
6
7
8
I: Current in amps

Fig 7

Measurement Circuitry
Discontinuity Method

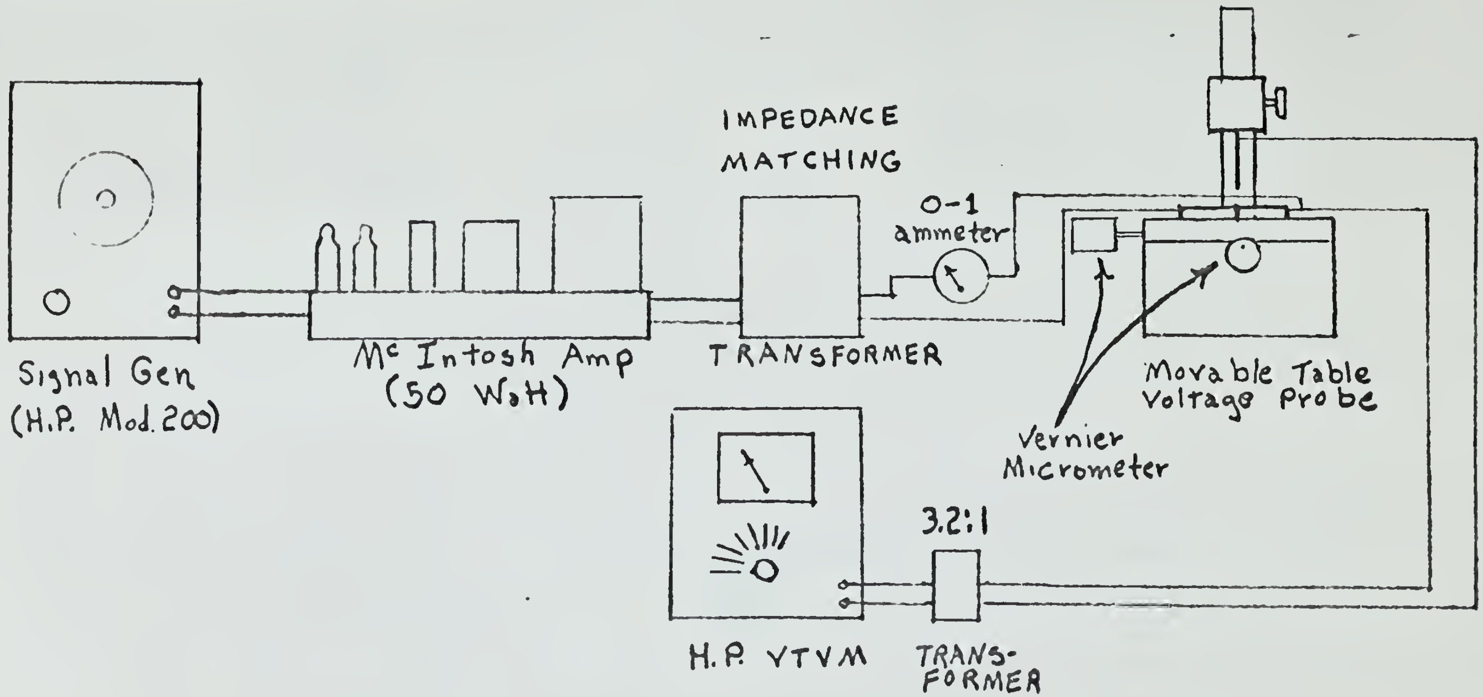
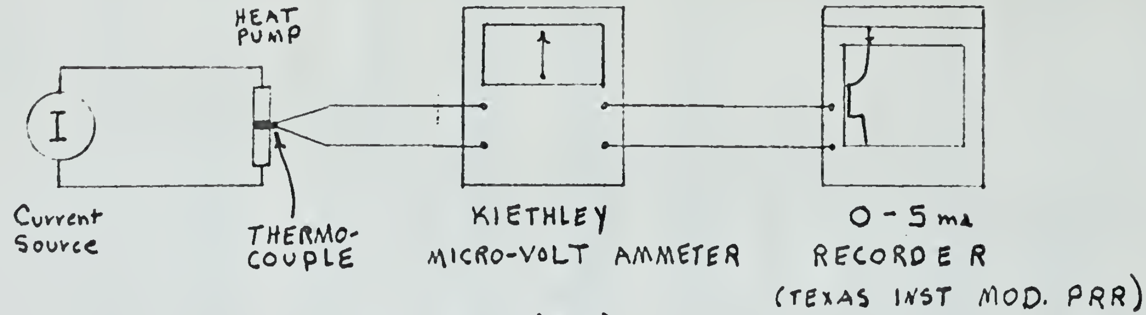
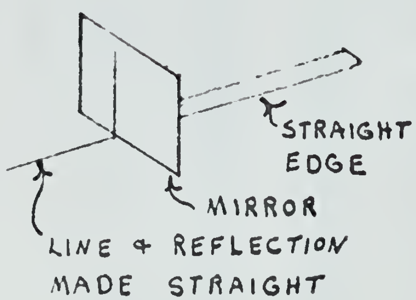


Fig 8

Measurement Circuitry
(TRANSIENT METHOD)



(9a)



TANGENTOMETER
(9b)

Fig 9

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